

AD A090649

LEVEL II

11 [Sept 80]

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ASTROINERTIAL NAVIGATION FOR CRUISE APPLICATIONS,

Robert B. Whitman / Manager of Special Projects

Northrop Corporation, Electronics Division
Hawthorne, California

Sept. 1980

ABSTRACT

→Astroinertial navigation systems provide the greatest accuracy and a bounded position error over an extended use-time and distance. These systems are autonomous, passive, non-jammable and automatic.

The key element of the system, the astroinertial instrument, is a three gimbal stable inertial platform with an integral two degree of freedom day-night star tracker that operates automatically world wide.

The system provides navigation, guidance, and control with the best accuracy available in any self-contained navigation system, from subsonic through hypersonic speeds. The present operational system described in this paper, NAS-26, provides bounded cruise navigational performance--better than 1,000 ft. CEP--throughout flights of short or long duration (specific performance classified).

The system weighs 184 pounds, volume is 3.9 cubic feet, and has a proven reliability of over 300 hours MTBF.

The NAS-26 system provides both navigation and guidance, and can also control and point other on-board avionics and sensors with the best accuracy available in any operational self-contained navigation system, from subsonic through hypersonic speeds. The system described provides bounded cruise navigation performance--better than 1,000 ft. CEP--throughout flights of short or long duration (specific performance classified).

A next generation system with improved performance is also described.

INTRODUCTION

For thousands of years man has relied on the stars as a primary source for determining his position on the surface of the earth. The United States' first intercontinental missile, the SM-62 Snark, used the first automatic astroinertial navigation system with three telescopes to overcome the inadequacies of the gyros and accelerometers of the 1950's to bound position errors to 1.4 nautical miles. The system to accomplish this weighed almost a ton with reliability that was in hours or tens of hours.

Today, thirty years later, Northrop has a fourth generation astroinertial operational system, the NAS-26, with performance, weight, and reliability that are each improved by a factor of over ten to one from the original Snark system. What is more surprising in our chaotic economy is that today's NAS-26 System is lower in production price than the Snark System of the 1950's. The NAS-26 system is shown in Figure 1.

PERFORMANCE

The NAS-26 astroinertial systems underwent an extensive flight test program in 1977. At the conclusion of the flight testing, the system was declared fully operational and in complete compliance with the performance specifications. Table 1 below shows the unclassified performance capabilities that may be released. Obviously, the actual

SUMMARY

Northrop has been building astroinertial navigation systems for over thirty years. These systems have been fully operational for over fourteen years and have logged over 35,000 hours of operational flight performance. The NAS-26 system described in this paper is the fourth generation system following Snark, Skybolt, and classified programs.

Astroinertial systems provide the greatest accuracy and a bounded error over an extended use-time and distance. These systems are autonomous, passive, non-jammable and automatic.

The key element of the NAS-26 system, the astroinertial instrument, is a three gimbal reference platform with an integral two degree of freedom star tracker. The reference platform contains two two-degree of freedom gyros and three accelerometers. The highly accurate star tracker provides correction of inertial platform errors by precisely tracking an average of three stars per minute, day or night, at any altitude. The system tracks down to +3.5 magnitude stars and bright stars in backgrounds up to 8,000 foot-lamberts. The stellar ephemeris provides a minimum of two star availability, world wide, with six to ten stars typically available.

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Secret classified performance capabilities are better.

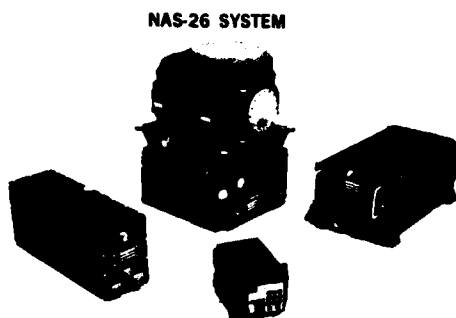


Figure 1

Table 1 NAS-26 Performance

Accuracy

Astroinertial.....	less than 1,000 ft. CEP for (occasional flights up to 10 hours. star-tracking)
Inertial.....	less than 0.5 n.mi./hr. (no prior star-tracking)
Velocity.....	less than 0.5 ft./sec.
Attitude Readout.....	better than 25 arc sec.
Reliability.....	better than 800 hrs. MTBF

REVIEW OF ASTROINERTIAL NAVIGATION

Before discussion of the NAS-26 System specifically, it seems appropriate to discuss the unique features of astroinertial navigation as employed in various Northrop systems.

The astrotracker is mounted integral with the inertial platform, as shown in Figure 2, with complete freedom in azimuth and essentially 0° to 90° in elevation. The primary key to the astroinertial system's excellent performance is the integral system, namely the ability to calibrate the star line-of-sight directly against the inertial accelerometer null reference frame.

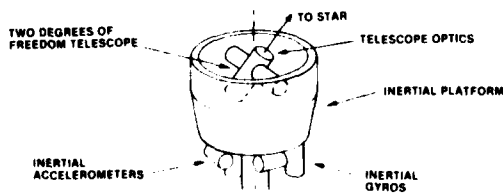


Figure 2 NAS-26 Astrotracker

The inertial platform provides instantaneous navigation data; i.e., velocity, heading and position. The astrotracker provides precise position updates, accurate heading, and calibration of gyro drift rates for near perfect gyro performance. The composite hybrid system results in bounded position performance that is essentially independent of flight time with only second order noise growth.

The NAS-26 system has a stellar ephemeris of 61 stars permanently stored in the computer. This provides a minimum of two star availability, world wide, day or night. Normally six to ten stars are available at any one time. The system will automatically sequence through in order each star within the field of view and then continuously repeat the cycle. The astrotracker tracks star magnitudes from -1.46 to +3.5 and in sky backgrounds of 8,000 to 430 ft-lamberts, respectively. The system automatically excludes stars that are within 12.5° of the sun, within 3° of other stars of similar magnitude, or near planets or the moon. Also, once per second a test is made to verify that the star is within the window field of view under conceivably changing vehicle attitudes.

The sequence of operations in star tracking is:

- Read sidereal (solar) time from the computer clock
- Determine present position from the computer
- The computer identifies catalog stars in field-of-view
- The computer selects brightest trackable star within the field of view
- Set photosensor gain for selected star magnitude and calibrate photosensor on built-in isolite source
- Open shutter and measure sky-background light-level in star vicinity
- Set scan rate for star magnitude and measured sky background
- Commence search.

The NAS-26 astrotracker search pattern is shown in Figure 3. The aspect ratio and size of the search pattern depends on the data provided from the Kalman filter. In simple terms the aspect ratio depends on the system uncertainties at the time.

When a star signal is detected in the search, the astrotracker changes to the confirmation mode. The primary purpose of this mode is to verify that the signal is in fact the star and not noise. The confirmation mode accomplishes this by generating a horizontal pattern requiring four detections in five passes and that the magnitude of the signal is correct for the particular star.

Once the confirmation mode has verified that it is the star, the astrotracker switches to the track mode (star position determination). Ten horizontal and ten vertical passes are made at the star

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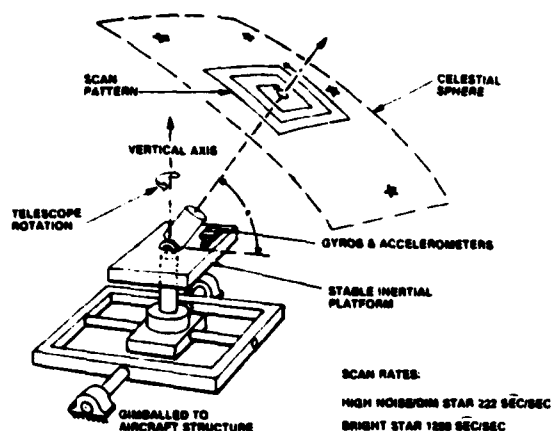


Figure 3 Astrotracker Search Pattern

with eight detections out of ten required. The resolver data for the detections are averaged to provide the best estimation of the true star line of sight. The standard deviation of a single star line of sight determination is better than three arc sec. (specific data classified).

At this point the next brightest star is selected and the process repeated automatically. After reading the above one would expect this to be a time consuming process; however, the NAS-26 system tracks an average of three stars a minute for the entire flight. Again the system tracks day or night, consistently tracking at sea level in daylight.

The star line of sight data is provided to the 18-state Kalman filter to update vector estimates of:

- Positions
- Platform Tilts
- Velocities
- Heading
- Gyro Drifts
- Accelerometer Null Bias
- Star Tracker Elevation Bias.

The net result is a navigation system completely self-contained, independent of ground fixes with: (1) bounded position performance of better than 1,000 ft. CEP (specific performance classified) for flights of up to ten hours, (2) star calibration of gyro drift rates permitting significantly improved free inertial performance if cloud cover were to occur, and (3) extremely accurate heading-velocity-attitude data for weapon delivery or sensor pointing or aiding.

FUNCTIONAL DESCRIPTION

The NAS-26 Astroinertial System may be described as a hybrid inertial navigation system that utilizes frequent star measurement updates in the stellar navigation mode. Inertial only navigation is used as a back-up degraded mode and/or in conditions where stars are not visible due to total cloud cover.

The NAS-26 provides continuous navigation, velocity, and attitude reference information. It is designed to interface with other avionics, such as Air Data Computer, Magnetic Compass, Flight Director Unit, Horizontal Situation Indicator and other display elements.

It also provides automatic vehicle guidance through control of the autopilot, automatic sensor control, sensor stabilization, image motion compensation, and a data reference base.

When interfaced with the Compass and Airspeed Units, it provides the following modes of navigation:

- Astro-Inertial-Airspeed
- Astro-Inertial
- Inertial Only
- Dead Reckon
- Attitude Heading Reference.

Initially, present position is supplied by the operator via navigation control display unit; thereafter alignment, both ground and airborne, and navigation, can be fully automatic. Highest priority is given to the most accurate navigation mode attainable. Alternatively, the operator may select the mode desired.

The inertial-computer system is configured in a wander azimuth, local gravitational mechanization, a choice reflecting the dependence on stellar-inertial as the primary mode. The star ephemerides for 61 stars are permanently stored in computer memory, thereby providing automatic 24-hour celestial navigation reference without geographic limits. Star ephemeris tables are updated (re-filled) annually. The star tracker, in addition to "bounding" position errors during its operation, also provides precision gyro drift rate calibration which contributes to significantly improved inertial-mode performance if this mode is required, as, for example, during periods of cloud cover. This star-calibration of the inertial gyros persists long after interruption of star tracking.

NAS-26 includes a Kalman filter software mechanization. This filter process, used for ground and air alignment, for stellar-inertial, and for inertial navigation modes, is an 18-state variable Kalman mechanization that operates in real time in

the computer and determines the relative weightings to be placed on the measurements. When airspeed is used as a velocity data source, for example, optimal estimates are fed back to correct both systems. Similar operations on the stellar measurements, barometric altitude, etc., provide extremely accurate navigational performance in the primary modes and provide optimized transition to degraded modes in the event of loss of any of the subsystem elements or by virtue of unavailability of cloud-free line of sight to the stars. At 25,000 ft. the worldwide mean probability of a clear line of sight is 68 percent at any instant of time, and improves rapidly to 100% as altitude increases. As implied above, the system maintains accuracy with intermittent tracking.

There is a large variety of output signals available from NAS-26. These outputs are computer controlled and are, therefore, software flexible. The use of the signals includes steering signals to enable great circle, heading, and point steering in addition to the conventional situation and navigational displays. Most of the outputs are available for stabilization, mode control, motion compensation, data annotation, etc., of sensor systems. Therefore, the NAS-26 System can operate as a complete automated guidance system, not just as a navigation system.

The NAS-26 also serves as a source for an accurate reference data base for inflight vehicle parameters. The data available includes vehicle attitude, velocities (vertical, crosstrack, ground speed), heading, acceleration (three axis), distance to destination, distance/bearing to points of interest, crosstrack range, sensor mode, etc.

Figure 4 shows a simplified NAS-26 system block diagram.

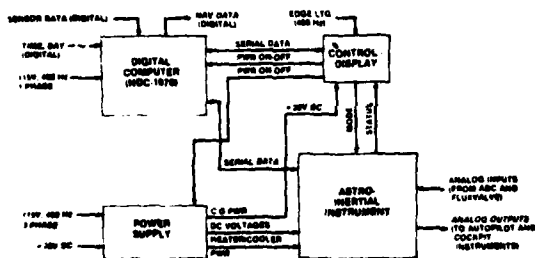


Figure 4 NAS-26 Simplified Block Diagram.

SYSTEM CONFIGURATION

The NAS-26 consists of four major assemblies (LRU's): the Astroinertial Instrument (AI), Digital Computer, Power Supply Unit (PSU), and Control Display Unit (CDU) (Figure 5).

The NAS-26 electronic design features are:

- Serial Communications for minimum inter-LRU wiring

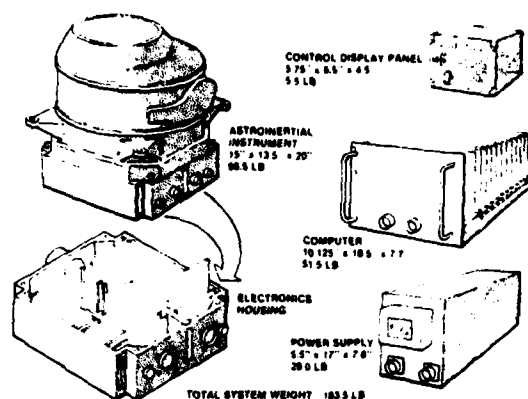


Figure 5 NAS-26 System

- Hybrid Microelectronics for reduced size and weight, and increased reliability
- Comprehensive BITE to assure fault detection and to enhance flight safety
- Partitioning into functional entities to facilitate isolation and to simplify LRU shop testing
- Use of worst-case practices to insure reliability and long life.

ASTROINERTIAL INSTRUMENT (AI)

The NAS-26 Astroinertial Instrument (AI) is an inertial measuring unit consisting of an enclosed three-gimbal stable reference platform and star tracker.

The AI is constructed in three main sections: a middle support housing consisting of the gimballed stable reference platform and star tracker; an upper cover fitted with an optically polished viewing window for the star tracker; and a lower housing containing related electronic circuitry and a recirculating air temperature control system operating across a Peltier thermoelectric heat exchanger, cooled from externally supplied air.

The middle housing contains the gimballed stable platform and the astrotracker. The order of gimballing inward from the middle housing support is: inertial roll, pitch and yaw, star tracker azimuth, and star tracker elevation. Roll, yaw and azimuth gimballing have complete rotation freedom; pitch motion is mechanically limited to $\pm 85^\circ$; elevation motion is limited to -2° to $+100^\circ$. Rotational torque is applied to the gimbals and tracker axes in accordance with computer commands by pancake-type direct drive DC torque motors. The gimbals and tracker axes are also equipped with pancake-type multipole resolvers for angle pickoffs and gimbal angle transformations. Transmission of electrical signals and power between the instrument housing, the gimbals, and the astrotracker is achieved by means of slip rings. These slip rings are mounted integrally within each gimbal axis.

The inertial platform is a bowl shaped casting having a central hub section extending downward from the bowl and several web frames radiating from the hub for mounting gyros and accelerometers. Fixed in the inertial platform assembly are two two-degree-of-freedom precision position gyros and three single-axis pendulous proof-mass accelerometers arrayed with their sensitive axes paralleling the reference axis of the platform. The platform assembly rotates in yaw about a vertical axis in the base of the pitch gimbal.

The astrotracker assembly can best be visualized as a second platform similar in material and shape, and smaller in size than the inertial platform. The major components of the astrotracker are installed within the tracker bowl, whereas the inertial platform components are mounted in web frames below the platform bowl. The tracker bowl is rotatable about a vertical axis relative to the inertial platform. The axis is co-linear to the platform yaw axis; however, it rotates independent of platform yaw motion, permitting azimuth rotations of the astrotracker opposite to or at different rates from those of the platform.

The star pointing telescope is mounted trunnion-fashion within the tracker bowl so that the telescope can be rotated in elevation about a horizontal axis. The telescope optical barrel is mounted on one side of the trunnion and the photo sensor and shutter are mounted on the opposite side, effecting a counterbalance. An alignment mirror, whose normal is parallel to the optical axis and perpendicular to the elevation axis of the telescope, is located near the outer end of the telescope.

The optical barrel of the star pointing telescope is 2 inches in diameter and about 2.5 inches in length. It is a modified Cassegranian telescope consisting of a primary aluminized mirror, a doublet lens backed by a secondary mirror, a folding mirror and field stop re-imaging lens system.

The primary mirror in the telescope base reflects the field of view into the secondary mirror. The secondary mirror is centered in the objective aperture and reflects the field onto a diagonally positioned flat mirror. The diagonal mirror folds the converging field 90 degrees and directs the rays, through an 0.10 inch aperture in the side wall of the telescope barrel, into the field stop assembly. A primary focus is achieved in the 0.0036-inch diameter opening of the field stop, after which a re-imaging lens directs the rays through a window in the electronic photo sensor case. A secondary focus occurs on the photocathode of the multiplier. The use of glare shades and optically absorbent coatings optimize the light perception of the telescope optics. The instantaneous field of view of the telescope is 40-arc seconds.

To minimize the entry of spurious light into the astrotracker, the telescope and photomultiplier on the elevation shaft are fitted with a shield having an opening only for the telescope barrel. In addition, the tracker bowl incorporates a domed

sun-shade with an open slot for telescope visibility (similar to the viewing slot in an astronomical observatory). To avoid saturation of the photosensor by excessive light entering the telescope, a solenoid-operated shutter closes over the window of the photo-multiplier case when not actually scanning, or whenever the sky brightness exceeds a predetermined level, such as scanning in close proximity to the sun.

The photomultiplier contains a photo-cathode located such that the optically directed rays from the telescope fall upon it. The signal collected from the anode is used as the input to an electronics package mounted near the base of the photomultiplier beneath the sunshade. A buffer amplifier, filter and preamplifier comprise the phototube electronics package. The output of this preamplifier is used in the detection circuitry of the tracker electronics located in the lower housing.

The upper housing is a cover fitted with an optically polished viewing window. A 95-degree cone of vision is attainable through this nine-inch diameter astro-window.

The lower housing contains those electronic circuits related to the AI function which are not thermally sensitive. These include the tracker detection and servo electronics, platform electronics, interface electronics, and the digital-to-analog and analog-to-digital conversion electronics that, along with a 2,000 word micro-processor, provide the communications and interface circuits with the Digital Computer. The lower housing contains a blower and heat exchanger structure to provide cooling by drawing ambient air through the housing.

The NAS-26 uses two Kearfott Gyroflex Mod 2 two-degree-of-freedom dry tuned gyros and three Kearfott Model 2401 accelerometers. See Table 2 and Figure 6.

Table 2 NAS-26 Gyro Parameters

Random Drift ($^{\circ}$ /hr) 1σ (10 hrs)	.006
Fixed Restraint ($^{\circ}$ /hr) p-p, day-day	.02
Mass Unbalance ($^{\circ}$ /hr/g) p-p, day-day, 30-90 days	.03
Anisoelastic Drift ($^{\circ}$ /hr/g ²) max.	.015
Temperature Sensitivity	
- FT ($^{\circ}$ /hr/ $^{\circ}$ F)	.002
- MU ($^{\circ}$ /hr/g/ $^{\circ}$ F)	.004
Volume (Cubic inches)	5.5
Size	2.1" dia. x .8" length
Weight (oz)	8
Settling Time (min)	1
Operating Life (hrs)	15,000

In the event of a Digital Computer failure, the NAS-26 System is mechanized such that the system gracefully degrades to an Attitude Heading Reference System (AHRS) with the inertial platform stabilized by the AI electronics. The AI electronics is also mechanized such that in case of



Figure 6 NAS-26 Inertial Components

failure of the platform-related circuitry, the magnetic heading from the flux valve is routed directly to the HSI through minimal signal conditioning circuitry.

POWER SUPPLY UNIT

The NAS-26 Power Supply Unit (PSU) is the power source for the AI electronics and the CDU and also supplies power for the AI Peltier thermoelectric heat exchanger.

The PSU includes power on/off sequencing and built-in test equipment (BITE) features to monitor and protect the PSU, as well as other LRUs, from over-current and out-of-tolerance conditions.

The primary power input to the PSU from the vehicle is 115V, 400 Hz, 3 phase.

The PSU conditions, controls, regulates and distributes the power to the AI and CDU; the computer receives power directly from the vehicle. The PSU supplies ten (10) separate dc voltages and 400 Hz blower power to the AI electronics section, two (2) dc voltages for the thermoelectric heat exchanger and +28V to the CDU.

DIGITAL COMPUTER

The Northrop NDC-1070 Computer provides the computation/data processing functions for NAS-26. While the NAS-26 is fully designed to interface with the NDC-1070, it is possible, in order to meet other application requirements, for NAS-26 computations to be performed by another suitable digital computer available to the application.

The NDC-1070 is a fully qualified, military, general purpose digital computer for airborne applications requiring high processing rates and high speed throughput capability. Specifically designed for the military operational environment and flight proven, the NDC-1070 is mechanized using TTL MSI logic circuits and magnetic core memory. Functionally, the NDC-1070 provides full

single and double precision logical and arithmetic capabilities, roll table mechanization, and high-speed multiple shift operations. In addition, a high throughput rate is achieved through direct memory access and provision is made for a full complement of efficient program interrupts, indexing and subroutine access features. A summary of the NDC-1070 characteristics is given in Table 3.

Table 3 NDC-1070 Computer Characteristics

Clock Frequency	4.5 mHz
Memory Type	Magnetic cores; non-volatile, random access, DRO
Size	32,768 or 65,536 words
Word Length	16 Bits
Cycle Time	2.0 Microseconds
Access Time	1.0 Microseconds
Arithmetic Mode	Serial, 2 bits at a time
Number System	Binary, fixed point fractional; with negative numbers in twos complement form
Data Formats	16 bits (single precision) or 32 bits (double precision)
Add	2 Microseconds - Inter-register (16 bits) 6 Microseconds - 16 bit memory-register
Multiply	6 Microseconds - Inter-register (16 bits) 8 Microseconds - 16 bit memory-register
Total Instructions	73
Instruction Formats	16 bits (short) or 32 bits (long)
Addressing	Single memory address per instruction, direct addressing to 65,536 words

A chronometer is not required as airborne equipment with NAS-26. The chronometer is used as aerospace ground equipment and is brought to the vehicle to initialize NAS-26 system time in the NDC-1070 computer. The computer maintains time through power dropouts for 15 minutes with an internal battery.

CONTROL DISPLAY UNIT (CDU)

The NAS-26 Control Display Unit gives the operator the ability to interface with the navigation system, control the navigation operating mode, change the sensor control parameters, and change the flight route. The operator may also effectively display many parameters of interest.

A combination of fifteen keyboard buttons, one rotary switch and one incremental switch allows the insertion or display of parameters as listed below. The panel includes three alphanumeric displays, mode displays, and status displays.

The status displays include star tracking status, temperature status, and system malfunction status.

The alphanumeric displays are able to display, as a minimum, the following data:

- Present Position - Latitude, Longitude
- Time and Day
- Heading
- Altitude
- Sensor Control Point (CP) Data - Ident. No., Latitude, Longitude, Altitude, Range
- Verification Fix Point (FP) Data - Ident. No., Latitude, Longitude, Altitude, Range
- Destination Point (DP) Data - Ident. No., Latitude, Longitude, Altitude, Range.

The following data is capable of being inserted through the panel:

- Latitude
- Day
- Longitude
- Altitude
- Heading
- CP, FP, and DP control data
- Time

COOLING AND POWER

Cooling

The cooling requirements for NAS-26 are as follows:

Astroinertial Instrument (Hermetically Sealed Section)

Inlet Air Temperature 30°F to 90°F
Inlet Air Flow Rate 2 to 5 pounds/minute

Power

The electrical power required for the NAS-26 is as follows:

	Average (Watts)	Peak (Watts)	
AI & PSU	500	800	3Ø 400 Hz
Digital Computer	235	270	1Ø 400 Hz
CDU	50	70	28 VDC
Total	785	1140	

Calibration

The NAS-26 Astroinertial Instrument (AI) is calibrated at the factory using specialized factory checkout equipment. This calibration is accomplished with the AI middle housing (containing the inertial platform and tracker assemblies) sealed under internal thermal control, and using the AI electronics for platform and tracker control. Thus, the AI is calibrated in its operational environment without simulation of hardware or thermal control. Calibration is accomplished under control of a microprocessor and calibration software that connects to and controls the AI, the tilt table, and autocollimator light source. The parameters that are calibrated include the internal light reference, telescope resolver angular errors, gimbal resolver angular offsets, and the accelerometer and gyro parameters. The accelerometer and gyro parameters include null bias, scale factor, misalignment, nonlinear corrections, drifts, etc.

Field verification tests are made periodically on the AI and if the parameter is found to exceed specification, and not correctable in the field, the AI is returned to the depot for recalibration.